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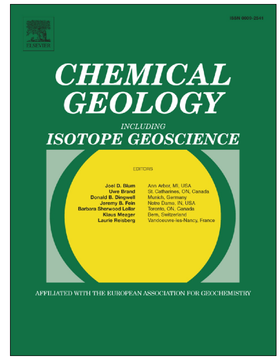

Soil functions and ecosystem services research in the Chinese karst Critical Zone

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Title: Soil functions and ecosystem services research in the Chinese karst Critical Zone

Running Title: Review of Chinese karst CZ soil research

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Abstract

Covering extensive parts of China, karst is a critically important landscape that has experienced rapid and intensive land use change and associated ecosystem degradation within only the last 50 years. In the natural state, key ecosystem services delivered by these landscapes include regulation of the hydrological cycle, nutrient cycling and supply, carbon storage in soils and biomass, nutrient cycling, biodiversity and food production. Intensification of agriculture since the late-20th century has led to a rapid deterioration in Critical Zone (CZ) state, evidenced by reduced crop production and rapid loss of soil. In many areas, an ecological 'tipping point' appears to have been passed as basement rock is exposed and 'rocky desertification' dominates. This paper reviews contemporary research of soil processes and ecosystems service delivery in Chinese karst ecosystems, with an emphasis on soil degradation and the potential for ecosystem recovery through sustainable management. It is clear that currently there is limited understanding of the geological, hydrological and ecological processes that control soil functions in these landscapes, which is critical for developing management strategies to optimise ecosystem service delivery. This knowledge gap presents a classic CZ scientific challenge because an integrated multi-disciplinary approach is essential to quantify the responses of soils in the Chinese karst CZ to extreme anthropogenic perturbation, to develop a mechanistic understanding of their resilience to environmental stressors, and thereby to inform strategies to recover and maintain sustainable soil function.

Keywords: karst, critical zone, China, soil processes, soil degradation, ecosystem services

Contents

1. Introduction: soil research in the Chinese karst Critical Zone

Soil degradation across China is a pervasive problem that is a major constraint to achieving a sustained increase in agricultural production to support the growing human population, estimated to reach 1.44 billion by 2024 (UN, 2017). The current population of 36 million in southwest China are amongst the poorest in the country with regional gross domestic product (GDP) at less than 50% of the national average (Huang et al. 2008). The most economically-deprived in the region are farmers who forge a living from cultivation of the characteristically thin soils overlying carbonate rocks in the sub-tropical karst ecosystem that covers ~0.51 million km^2. Land available for farming is constrained by the distribution of pockets of soil of adequate depth between rock outcrops. Here, widespread deforestation of the steeply sloping topography has caused accelerated erosion of soil by water, especially during monsoonal downpours (Zhang et al. 2011a; Chen et al. 2012a; Bai et al. 2013; Peng et al. 2016). In addition, soil function and subsequent ecosystem service delivery from soils is negatively impacted by poorly managed cultivation (Richardson & Kumar 2017), including unbalanced inorganic fertilization (Figure 1) to support continuous rotational cropping and manual consolidation of dwindling soil stocks by farmers (Figure 2). In many areas, a tipping point (i.e. the 'point of no return', where soil function is effectively lost due to insufficient mass and/or biological viability) appears to have been passed as rapid and intensive land use change over several decades has caused widespread landscape degradation, ranging in severity from diminishing soil cover to discontinuous regolith to large areas of bare rock, described as 'rocky desertification' (see Text box, Figure 3, 4; Huang & Cai 2007; Wang et al. 2004a, 2014; Chen et al. 2011b; Gao et al. 2013). For example, between 1974 to 2001 rocky desertification in Guizhou Province proceeded at a rate of ~120 km^2 yr^{-1} (Huang & Cai 2007). Recently, Jiang et al. (2014) estimated that 5.8% of the southwest China karst is rocky desert (Table 1). The ramifications of the widespread rocky desertification in southwest China karst are profound at the human-scale and may have significant larger-scale consequences including changes in evaporation which could affect the timing and location of monsoon rains (Gao et al. 2013).

Progressive soil degradation in Chinese karst landscapes diminishes *soil functions* including nutrient cycling; provision of food, fibre and fuel; carbon sequestration; water purification and soil containment reduction, climate regulation; flood regulation; and habitat for organisms. Consequently, the delivery of regulating, supporting and provisioning *ecosystem services*, e.g. regulation of the hydrological cycle, nutrient cycling and supply, carbon storage in soils and biomass, nutrient cycling and biodiversity (Field et al. 2015), is severely compromised. Of profound importance to the local human population of the Chinese karst, the provisioning ecosystem service of food production is critically affected by soil degradation and presents as persistently poor and declining crop yields (Yuan 2001; Lal 2002; 2015; Liu et al. 2006; Wang et al. 2004a; Zhang et al. 2013). Sustainable solutions to land management are urgently required to restore the degraded karst landscapes of southwest China, potentially including abandonment and economic compensation, and are integral to lifting the local population out of poverty (Quine et al. 2017); thus, the 'Grain for Green Programme' (GGP) was introduced in the region in the 1990s (Liu et al. 2008; Uchida et al. 2005). Abandonment of sloping agricultural land is a key recommendation, with the expectation for the unmanaged regeneration of natural vegetative communities to mature, species-diverse forest, and the ultimate rejuvenation of degraded soils. However, little is known about the geological, hydrological and ecological processes which control soil functions in these landscapes and how best to manage them to optimise ecosystem service delivery. The key question for regeneration and sustainable management of the karst landscapes in the region is thus "how can the highly heterogeneous critical zone resources be restored, to enable sustainable delivery of ecosystem services?"

How the geological evolution of the CZ has established ecosystem functions and the foundations for CZ sustainability is a fundamental CZ science question (Banwart et al. 2013). We contend that karst landscapes represent an end-member on the spectrum of sensitivity of natural ecosystems to human perturbation in which unsustainable land use is causing catastrophic change in ecosystem function from which the systems are unlikely to recover on relevant management timescales. This review paper specifically explores recent research on Chinese karst ecosystems since the early 1980s through a multidisciplinary CZ lens on specific soil processes (e.g. weathering of minerals, percolation of water, rooting, decomposition) and soil functions and ecosystem service delivery from soil (see recent reviews by Bouma (2014) and Adhikari and Hartemink (2016)). It focusses on the complex biogeochemical-physical processes that combine in the karst CZ, i.e. from the vegetation canopy down to the epikarst (the weathered zone of enhanced porosity on or near the surface) to transform rock and biomass into soil that in turn supports the function of the terrestrial biosphere, including human well-being (White et al. 2015). Particular emphasis is placed on the potential for the recovery of key soil functions that deliver ecosystem services after abandonment of agriculture under the GGP (see Text box).

2. The imbalance between soil formation and soil loss by erosion in the Chinese karst CZ

Soil quantity is determined by the balance between the rates of pedogenesis and losses by erosion, and both are strongly affected by numerous factors including geomorphologic position, vegetation cover, and management. The iconic (unmanaged) Chinese karst landscape is characterised by evergreen and deciduous broad-leaved mixed forest covering steep slopes, where diverse microhabitats arise from the complex mosaic of rock and soil and dynamic hydrology that strongly influences the spatial distribution of soil, water and nutrients. The distinctive hydrology and landforms arise from the combination of highly soluble carbonate lithologies and well-developed secondary porosity, characterised by a surface-underground ‘double layer’ of rugged, complex surface terrain intimately connected to large subterranean drainage networks, characterised by sinkholes, sinking streams, closed depressions, caves and fissures (Williams 1987; Cao and Yuan 2005; Peng & Wang 2012; Dai et al. 2015) (Figures 3 and 5).

2.1 Bedrock weathering and soil formation

The production of soil mineral particles by bedrock weathering is slow, therefore, soil formation is generally considered to be most significant over geological, rather than human, timescales (Wei 1996). The substantial rainfall of the sub-tropical monsoonal climate of southwest China promotes rapid carbonation (although higher temperatures will slow the rate as carbon dioxide (CO_2) is less soluble at higher temperatures), and subsequently, only minimal amounts of undissolved mineral particles are available for soil formation in karstic systems of the region. Therefore, in the absence of aeolian deposition, soil formation in karst areas depends on “impurities” within the bedrock, predominantly silicate minerals, which provide both a structural matrix and additional elements, many of which are essential macro- and micro-nutrients (Wang et al. 1999; Moore et al. 2017). Wang et al. (1999) examined bedrock from five sites across Guizhou and Hunan provinces and found 11.6 – 38.8% non-carbonate residual mineral content in the limestones and 0.6 – 4.0% residual content in the dolostones. They correlated these contents with mineral and elemental contents in the overlying soils to conclude that the soils were formed from the bedrock impurities and not via deposition of transported material. Non-carbonate mineral contents can vary even within a single outcrop as observed by Moore et al. (2017) who found adjacent beds in Puding County, Guizhou, with 4, 25, and 33% non-carbonate mineral contents. Based on the abundances of non-carbonate (largely silicate) mineral impurities in the bedrock of the karst region of southwest China, up to 8000 years is required for ~1 cm of soil to form (1.3 – 5.0 mm ka^{-1} weathering rate) from dissolution of the carbonate bedrock under present climatic conditions, without erosion or other anthropogenic perturbations (Wan 1995; Wang et al. 1999; Li et al. 2002). An average rate of soil formation was estimated for the central Guizhou karst region at up to 3.7 mm ka^{-1} (Wan 1995). However, anthropogenic perturbations such as acidification by inorganic fertilizers, weathering rates and nutrient release can accelerate and become relevant at timescales with significance for local human populations (discussed below).

Rock-soil-water-atmosphere interactions and the transfer of energy and materials in karst environments are constrained by the mineralogy and chemical weathering of the bedrock. Zhu et al. (2008) divided the weathering-pedogenesis of carbonate rocks into three geochemical evolution stages based on the dominant processes occurring at different depths in karst soil profiles: (1) calcium (Ca), magnesium (Mg)-depletion and silicon (Si), aluminium (Al)-enrichment; (2) iron (Fe), manganese (Mn)-enrichment and (3) Si-depletion and Al-enrichment in subtropical regions. The rock-soil interface of carbonate rock weathering profiles is generally characterized by strong Si and Al enrichment and Ca depletion, with limited enrichment of Mg observed in some limestone profiles (Zhu et al. 2008), where Mg is retained in silicate minerals. Due to the low nutrient content (with the notable exception of Ca and Mg) of carbonate lithology, spatial variation in ecosystem productivity and CZ resilience to perturbation may be strongly controlled by the vertical and lateral distribution of non-carbonate (silicate) lithology. A positive spatial correlation was observed between soil nutrient content and non-carbonate (silicate) lithology in Guizhou (Chen & Bi 2011). Similarly, Wang and Zhang (2003) observed a correlation between the spatial distribution of carbonate rocks and rocky desertification in southwest China, with less rocky desertification observed in regions with higher percentages of non-carbonate rocks.

Biological controls on weathering rates and soil formation drive micro-scale geomorphological processes. The penetration of roots, roots hairs and fungal mycelia between mineral particles causes physical weathering and exposes mineral surfaces to other erosive forces (Figure 6), including associated chemical weathering caused by respiration, i.e. respired CO_2 dissolved into water forms carbonic acid (H_2CO_3), and the secretion of enzymes (e.g. carbonic anhydrase), organic acids and ligands (Li et al. 2005, 2009, 2012b). For example, a fungus of genus *Aschersonia* sampled from a colony growing naturally on limestone in the Nanjiang Grand Canyon in Guiyang accelerated calcite dissolution rates in laboratory incubations (Hou et al. 2013). Likewise, mycorrhiza play an important role in the dissolution of carbonate rocks to scavenge essential nutrients that are transported to host plant roots (Quirk et al. 2014). Arbuscular mycorrhizal fungi (AMF) appear to be less effective in weathering silicate rocks than ectomycorrhizal fungi (EMF), but little is known regarding their potential for promoting carbonate rock weathering, or their importance relative to roots (Quirk et al. 2014). Such mechanisms may be especially important in karst regions, where the paucity of mineral elements in carbonate rocks and the low soil mass (depth to bedrock) are significant limiting factors on Net Primary Productivity (NPP) (see section 3.2). The general observation is that the topography is the predominant influence on SiO_2 and CaO in soil, and the abundances of these mineral oxides in karst soils exert a primary control on the species diversity of vegetation, vegetation biomass, soil organic matter (SOM) and N cycling, and other soil properties (Du et al. 2014; see section 3.2).

Soil formation is typically considered to be most significant over geological timescales because of the low rate of production of stable soil mineral particles from parent material. However, where CZ perturbation alters the weathering rate and the nutrient release rate the impact of the perturbation could be important over much shorter timescales relevant to management (i.e. 10s to 100s of years). Therefore, land use may have a major influence on rock weathering rates and soil mineral contents, weakening the effect of natural biological controls over weathering rates and soil formation. Weathering intensity in sloping farmland and plantation forests in Chinese karst in Huanjiang County, Zhuang Autonomous Region of Guangxi was significantly increased compared to primary and secondary forest land uses, and concentrations of CaO, MgO, and P_2O_5 were significantly less, and Al_2O_3 and Fe_2O_3 contents greater, under management (Du et al. 2014). This suggests that the application of inorganic fertilisers which promote mineral dissolution and nutrient leaching by acidifying soils are likely to be more important than deep-rooted vegetation in controlling weathering in managed regions of karst landscapes. This is supported by the stable isotope signatures of dissolved inorganic carbon (DIC) in groundwater determined in Guangxi. These indicated that whilst carbonic acid accounted for the majority of carbonate dissolution, up to 20% was caused by sulfuric and nitric acids derived from the liberal use of mineral fertilizers directly or indirectly as atmospheric deposition, which ultimately accelerated carbonate dissolution (Chen & Jiang 2016).

Due to the low nutrient content of carbonate lithology, spatial variations in ecosystem productivity and CZ resilience to perturbation may be strongly controlled by the vertical and lateral distribution of non-carbonate (silicate) lithology. Li et al. (2017) investigated the dynamics of soil carbon (C) and nitrogen (N) contents during post-agricultural succession at

125 sites from cropland, grassland, shrubland, and secondary forest in areas underlain by dolostone or limestone in Guangxi Zhuang Autonomous Region. They reasoned that the more rapid dissolution rates of limestone could replenish lost Ca and associated soil C and N contents relatively quickly, suggesting that dolomitic systems are more vulnerable to the negative impacts of land-use change than limestone systems, and should perhaps be priorities for abandonment or restoration. However, it should be noted that possible differences in soil depth and land use intensity could exist between soils over contrasting lithology types and these were not assessed by Li et al. (2017). It has been demonstrated by Chen and Bi (2011) who noted a positive spatial correlation between soil nutrient content and non-carbonate (silicate) lithology in Guizhou. Nevertheless, this dependency has been poorly explored in the unique karst lithology of the Chinese karst where soil can occupy deep rock fissures. In order to achieve this, it is necessary to improve knowledge and understanding of the distribution of silicate minerals in interbedded silicate clastic rocks or as impurities in carbonate rocks in the CZ, and quantify the variation in long-term mineral nutrient release exercised by the distribution of silicate minerals.

2.2 Soil erosion and loss

Despite the magnitude of landscape degradation in southwest China, there are still very few studies that comprehensively assess soil erosion within the karst environments of the region (Li et al. 2011; Chen et al. 2011b; Peng & Wang 2012; Yang et al. 2011; Feng et al. 2016; Huang et al. 2016). Rocky desertification is evidence that soil is being lost at rates far in excess of replacement from the characteristic sloping topography (5-25°; Wang et al. 2004b; Huang & Cai, 2007; Jiang et al. 2009). For example, in central Guizhou, the average rate of soil loss by erosion is ~11.1 mm ka^{-1}, substantially greater than the rate of soil formation (up to 3.7 mm ka^{-1}; Wan 1995). Soil thickness tends to be thinnest on the higher slopes, whilst the lower slopes, such as those of karst basins, depressions or valleys, have obvious deposits of soil originating from the surrounding mountains. Bai et al. (2013) estimated the net erosion rates on the hillslopes in Shirenzhai catchment, Puding County, Guizhou using the catchment depression (i.e. the enclosed catchment basin). The authors estimated that 52.58 Mg ha^{-1} y^{-1} soil was eroded from 1979 to 1990, and 2.56 Mg ha^{-1} y^{-1} soil was eroded from 1991 to 2008. Bai et al. (2013) concluded that the increased estimated sediment yield for the period 1979 to 1990 was due to widespread deforestation in 1979 after land ownership change within the catchment. Since 1990, erosion rates have decreased, but principally because there is little remaining soil to erode as bare rock predominates across the catchment.

A prominent feature of the karst landscapes in the most extreme state of desertification is the rapid connection between the surface and sub-surface channels via underground drainage networks, e.g. pore fissures, crevasses and sink holes (Zhang et al. 2011a; Chen et al. 2012a; Peng et al. 2016). In this state, soil eroded laterally over the surface can be quickly lost to sub-surface channels. Furthermore, leaching of soluble N and cations from the thin, calcareous soils of karst systems may reduce the ability of the remaining soil to provide vital ecosystem services, for example, nutrient and water regulation and supply, carbon sequestration and food production (Song et al. 2017; Ma et al. 2018). Defining when a karst system is approaching this state would be advantageous for landscape management via interventions to prevent the tipping point being reached. Currently, the tipping point is uncharacterised biologically or chemically for karst soils, however, it is inferred that as the system approaches this state, a greater proportion of sediment transported in the subterranean network will be of near-surface origin. However, due to methodological challenges, the majority of studies to date have focused on surface erosion and have not quantitatively assessed underground losses. Furthermore, the erosion models that have been used in karst soils in China have primarily been developed based on soil erosion processes in non-karst agricultural lands.

Although the applications of soil erosion modelling for karst watersheds and river basins are limited, the number of studies is increasing. Modelling efforts by Xu et al. (2007), Xiong et al. (2009), Ni et al. (2010) and Wang (2011) showed good performances using established models (Universal Soil Loss Equation (USLE) and Revised Universal Soil Loss Equation (RUSLE)) in karst areas. These models predict annual potential total soil loss due to water erosion as a function of rainfall erosivity, land use, soil and agro-management specific settings, but have been developed and mostly used in non-karst regions, lacking any significant sub-terrain drainage characteristics. Hence, Geissen et al. (2007), Kheir et al. (2008), Xu et al. (2007) and Yang et al. (2014) extended the RUSLE model by including a karst desertification and rock infiltration index, which take into consideration the lithology, lineament density, karstification and drainage density. Similarly, Febles-Gonzalez et al. (2011) and Feng et al. (2014) used and revised another commonly used water erosion model, the Morgan–Morgan–Finney (MMF) model, for karst areas. Feng et al. (2014) predicted spatial distributions of soil erosion rates relative to land uses and slope zones in a karst catchment in Huanjiang (northwest Guangxi); the results showed that the simulated effective runoff and annual soil erosion rates of hillslopes agreed well with the field observations and previous quantified redistribution rates with caesium-137. Caesium-137, derived from the testing of nuclear devices in the past, is widely used as a sediment tracer of soil redistribution, providing information on medium-term (40-50 years) erosion rates (*cf*. Campbell et al., 1988; Walling & Quine, 1991; Quine & Van Oost 2007). The study estimated average effective runoff and annual erosion rates on hillslopes of the study catchment of 18 mm and 0.27 Mg ha^{-1} yr^{-1}, respectively, during 2006/07. Average erosion rates ranged from 0.10 to 3.02 Mg ha^{-1} yr^{-1} for different land uses, with the order of increasing magnitude: shrub land > other woodland > forested areas > grassland > farmland > non-vegetated areas (i.e. bare land), thus highlighting that human disturbances played an important role in accelerating soil erosion rates (Feng et al. 2014). In addition, Chen & Lian (2016) used the RUSLE model to predict soil erosion rates in Guijiang karst river basin, Guangxi. The authors estimated an average total soil loss from areas without rocky desertification as ~26%, rising to ~71% from areas with mild karst rocky desertification. Soil loss from areas with moderate rocky desertification was ~3%, largely due to the large percentage of exposed carbonate rocks and lack of soil in the karst terrains. In addition, Peng & Wang (2012) assessed the effect of land use, land cover and rainfall regimes on surface runoff and soil loss on karst slopes in Chenqi, Guizhou Province between 2007 and 2010. The amounts of surface runoff and soil loss on the karst hillslopes were very small compared to the non-karst areas. This was attributed to the dual hydrological structure in karst regions, with most rainfall being transported underground through the epikarst. Surface runoff and soil loss were affected by land management, vegetation cover, and rainfall intensity, with soil loss being greater in over-used pastureland during heavy rainstorm events. It needs to be recognized that the applications of soil erosion models described above for the southwest Chinese karst region only take water erosion into account. Hence, there exists the urgent need to consider more advanced models enabling estimates for both water and tillage erosion (e.g., WATEM-SEDEM, Van Rompaey et al. 2001) to allow more complete and spatially detailed total soil erosion assessments in these environments.

Soil erosion not only results in loss of soil mass and depth, but the preferential loss of the most biologically active surface soil results in significant impacts on soil properties even in high input agricultural systems in less challenging terrains (Quine et al. 1999; Kosmas et al. 2001; Quine & Zhang 2002; Van Oost et al. 2005; Beniston et al., 2015). There is some evidence that SOC stocks can be held in equilibrium by new SOC formation because SOC respiration rates are suppressed by low SOC content; and, some eroded SOC is replaced by new organic matter; if eroded SOC is conserved, there is potential for an erosion-induced net atmospheric sink for CO_2 (Van Oost et al. 2007; Li et al. 2015). However, the quality of the SOC must be considered as a component of SOM that promotes a range of soil quality parameters required for ecosystem recovery in degraded karst landscapes vulnerable to severe system degradation (Dungait et al. 2013; Quine et al. 2017). Changes in quality (i.e. composition) and quantity of SOM may inevitably influence soil degradation, agricultural productivity and food security (Srinivasarao et al. 2014; Janzen 2015).

Measuring the quantity and spatial distribution of SOM is essential for evaluating soil function and subsequently the potential for ecosystem recovery from perturbation. However, estimating large-scale SOM storage for soils with discontinuous distribution in the karst regions (Figure 2, 3 and 5) poses a challenge because C, nutrient and water stocks may be located in deep sediments within fissures in the epikarst (Figure 3). Incomplete replacement of eroded soil organic carbon (SOC) is most common, and soils exhibited a decline in SOC content in the areas experiencing erosion in the Puding watershed in Guizhou Province (Quine et al. 2017). In karst landscapes slow rates of production of soil material by weathering accompanied by surface erosion leads to loss of soil depth, loss of nutrients and SOC locked up in SOM (Wang et al. 2015a,b), including microbial biomass (Dungait et al., 2013; Turner et al. 2013), and associated reduction in soil structural stability (Le Bissonnais & Arrouays 2005), further increasing susceptibility to erosion by water. Furthermore, subterranean pathways for rapid water and nutrient and soil loss during precipitation events degrades surface soils and decreases NPP (Ma et al. 2018). The reduced soil depth and reduced SOM content of the eroded soils leads to significantly lower water holding capacity and maintenance of production under heightened moisture stress is at risk, which has further implications in terms of the soils capacity to maintain a plant community.

3. Plant adaptations to spatial resource heterogeneity in the Chinese karst CZ

Plant community succession plays an important role in vegetation recovery and dynamics in post-disturbance karst landscapes. A better understanding of the relationships between plant distribution, soil properties, and topography, e.g. location of water and nutrients, in karst regions may assist in determination of the driving forces of plant species distributions (Peres-Neto et al. 2006) and identify effective ecological restoration options in the region. In particular, investigating the linkages between root traits and soil water and nutrient status across the degradation gradient is critical to improving understanding of how CZ processes control ecosystem productivity, and allows for CZ science to be used directly to inform optimal management strategies. Overall, there is a growing emphasis on the need to extend the trait-based approach developed for understanding leaf physiology belowground to consider root systems (Pregitzer et al. 2002; Iversen 2014) and their association with soil microorganisms in the rhizosphere, including mycorrhiza, to promote plants species selection for accelerated regeneration by encouraging efficient use of available water and nutrients.

Considerable temporal and spatial variability in soil properties and topography is a common feature of karst environments in southwest China (Peng et al. 2008) and presents challenges to vegetative growth. Widespread loss and habitat degradation of natural forests in karst areas has led to numerous studies on plant communities (Yu et al. 2002; Su & Li 2003; Shen et al. 2005), species diversity (Tang et al. 2010) and the relationship with soil properties (Li et al. 2005; Hu et al. 2009). However, there remain conflicting reports of how differences in rooting depth affect access to water and nutrients in this highly heterogeneous landscape. It has been suggested that 90% of root biomass is in the top 20 cm in these soils (Ni et al. 2015), but vegetation distribution appears to be positively related to soil depth, especially where fissures exist in carbonate rocks. During dissolution, P and the other elements essential for plant growth are released in small concentrations and can accumulate in seepage water as it moves through the karst system leading to more elevated concentrations of nutrients in deep fissure soils than in topsoils (Zhongcheng 2000). This suggests that deep roots play a relatively important role in water and nutrient uptake (Figure 6) but further evidence is required to truly establish this relationship. Furthermore, understanding nutrient cycling in the CZ requires quantification of variation in mineral weathering rates and analysis of this variation with respect to soil and vegetation distribution, including the role of roots and microorganisms, e.g. mycorrhizal mycelia, in the weathering of bedrock (see section 2.1).

3.1 Water storage and availability in soil

Successful landscape regeneration through vegetation restoration efforts in the karst region of subtropical China relies on a detailed understanding of the spatiotemporal availability of soil water (and, by definition, soluble nutrients) in the complex karst geohydrology (Chen et al. 2010; Zhang et al. 2011b). The aspect and surface area percentage of outcropping rocks in undisturbed karst systems drives natural plant distributions (Du et al. 2015). Common aboveground adaptations to fluctuating water supply (see review by Chaves et al. 2003) are encountered in native plants of karst systems such as defoliation and dormancy in drought seasons (December), and changing water use efficiency (WUE) is revealed by $\delta^{13}C$ values of leaves that differ between species (Song et al. 2008a; Dungait et al. 2010; Nie et al. 2014). Karstic surface soil moisture positively correlates with the aboveground height of exposed bedrock because the outcrops encouraged water infiltration at rock-soil interfaces and generate microclimates through shading that lowers evapotranspiration in dry seasons (Li et al. 2014; 2016). However, belowground adaptations in root architecture likely dominate the success of vegetative colonisation in heterogeneous karst landscapes because the fluctuating climate and porous lithology create evolutionary pressures to adapt strategies to cope with water stress. The ratio of root-to-aboveground biomass in karst primary forests (0.37) is significantly greater than the mean ratios (0.26 – 0.07) reported for subtropical evergreen forests generally (Ni et al. 2015). The relatively poor above-ground biomass stocks in karst landscapes are further reduced by land degradation (Yang & Cheng 1991; Tu & Yang 1995; Zhu et al. 1995). Loss of SOM by incessant cultivation reduces the water-holding capacity of thin karst soils. Soil moisture at 5 cm depth in bare soil in rocky desertified fields was two-fold less than in coniferous and broad-leaved mixed forest within the same climatic region (Li et al. 2014), suggesting SOM management as a primary mechanism for landscape regeneration (Dungait et al. 2012).

There is evidence of water resource partitioning that decreases competition and promotes plant species' coexistence in karst regions (Rong et al. 2011). Shallow-rooted plant species tend to have well-developed lateral roots, with horizontal spatial expansion capability for a water (and nutrient) acquisition (Querejeta et al. 2007). Ni et al. (2015) found that the majority (~89%) of the root biomass of karst vegetation was located in the top 0 - 20 cm depth in five land cover types (grassland, grass–scrub tussock, thorn–scrub shrubland, scrub–tree forest, and mixed evergreen and deciduous forest) in Maolan, southern Guizhou Province. Although the majority of water is stored in the main soil profile, soil within deep fissures in the rock stratum may also be important sources of water (Guo et al. 2011) only accessible by deep-rooted plant species (Querejeta et al. 2006, 2007; McElrone et al. 2007; Schwinning 2010), and potentially through mycorrhizal associations in deep soil (de Araujo Pereira, 2018) though the latter has not been explored in karst soils. In Wangjiazhai catchment, Guizhou Province, shrubs took up to 100% of their water requirement water from the deeper subcutaneous zone in the dry season (Rong et al. 2011). Shallow- and deep-rooted plants can, therefore, coexist and avoid interspecific competition because their roots are vertically distributed, and have equivalent soil resource utilization (Jose et al. 2006; Nippert & Knapp 2007; Wanvestraut et al. 2004). Furthermore, some woody plants have dimorphic root systems that can access distinct shallow and deep-water sources, as revealed by ^{18}O isotope analysis (Nie et al. 2011; Deng et al. 2012), and the roots of specific grass species express morphological plasticity in response to changing and heterogeneous resource availability (Zhao et al. 2017). Considering the physiological adaptations of different plants to water stress may suggest novel options for improved management of vegetative recovery in degraded karst landscapes.

3.2 Soil nutrient cycling and availability

Understanding how native plant communities overcome nutrient limitation in the characteristically thin, nutrient-poor soils of undisturbed karst systems may provide solutions for the strategic restoration of degraded karst regions in southwest China, but the location of actual and potential bioavailable nutrient sources in the karst CZ is poorly understood. Low concentrations of N, P, K and other trace elements in porewater may place a strong constraint on the NPP of karst landscapes, especially in areas with high rates of rainfall (up to 2500 mm; Liu et al. 2014b). For example, the biomass of primary forest in Mulun National Nature Reserve, Guangxi was only 131 t ha^{-1} (Song et al. 2008b), far lower than that of non-karst forest within the same ecological niche, and considerably less than that of the desert edge or the north Taiga forest (Yang 1994). Consequently, karst trees show significantly decreased concentrations of multiple nutrients relative to Chinese plants generally (Liu et al. 2014a), suggesting that their growth could be limited by other nutrients in addition to N or P (Zhang & Wang 2009). For instance, zinc (Zn) concentration is 26-110 ppm in reference silicate rocks and 2-7 ppm in reference carbonate rocks (Thompson et al. 1970). The biogeochemical cycles of N versus rock-derived nutrients differ strongly. Phosphorus (P), potassium (K), Ca and Mg and other trace elements are originally derived from rock weathering, including rainwater and dust inputs (Jordan 1982; see section 2.1). The availability of P, K and other trace elements in karst systems in southwest China are limited by the low concentrations in carbonate rocks accompanied by high leaching rates under subtropical rainfall. Furthermore, P-limitation is exacerbated by strong adsorption and co-precipitation with Ca (Liu et al. 2014a; Du et al. 2011). Soil degradation and erosion of topsoil increases N limitation (Zhang et al., 2015), and could result in co-limitation by a range of nutrients in highly degraded areas. This has led to suggestions that promoting colonisation by leguminous N-fixing tree species could be effective in accelerating restoration of karst regions (Tian et al., 2008). It would increase N-inputs (directly and indirectly) through the generation of increased organic matter (i.e. plant litter) cycling through the soil system, sustaining a larger microbial community capable of carrying out a broader range of functions (Liu et al. 2007).

Plants can adopt a wide range of strategies for increasing access to limiting nutrients, including: (1) genome-size evolution that enhances DNA and protein building blocks needed for growth (Kang et al. 2015); (2) resorption of nutrients from senescent foliage that decreases nutrient loss (Du et al. 2011); (3) symbiosis of roots with arbuscular mycorrhizal fungi that enhances soil weathering (Thorley et al. 2014; Liang et al. 2015) or free-living or symbiotic atmospheric dinitrogen (N_2)-fixing bacteria (Liu et al. 2015a); and (4) SOM priming and mineral dissolution in rhizosphere soils by organic acids and enzymes exuded by fine roots and mycorrhizal hyphae (Strom et al. 2001; Clarholm et al. 2015; Pan et al. 2016). For instance, in the high pH soils of karst regions, there are suggestions that organic acid secretion from proteoid/cluster roots could be important in alleviating P limitation in tussock grasslands which form in the early stages of succession following abandonment (Vance et al. 2003; Péret et al. 2014). Most of the native plants in karst ecosystems are considered to form mutualistic associations with mycorrhizal fungi, involving C (photosynthate) transfer from the host plant to the fungus, and nutrients from the soil to the plant in return (Smith & Read 2010), but evidence of the extent of the relationships is poor. He et al. (2017) concluded that maintaining AMF diversity could be important for mediating N transfer directly from organic material, e.g. leaf litter, to host plants in N-poor soils, but there is conflicting evidence regarding whether the fungi are able to act as agents of saprotrophic nutrition (Tisdall et al. 1997; Wright & Upadhyaya 1998; Hawkins et al. 2000; Hodge et al. 2001; Tu et al. 2006). However, it is clear that the recycling of essential elements through litter decomposition seems to be particularly important for the nutrient budget of karst ecosystems. Increased tree species richness significantly accelerates nutrient release from leaf litter, which could in turn contributes to supporting high biodiversity in the forest of harsh karst habitats, driving non-additive effects on decomposition (Liu et al. 2016). In particular, the presence of deciduous broad-leaved trees in karst ecosystems were found to significantly contribute to nutrient cycling, by promoting more rapid decomposition of evergreen broad-leaf litter. Liang et al. (2016) reported that AMF, N_2-fixing bacteria and plant community composition differed significantly between vegetation types as soil nutrient levels (available P, total N and SOC) and plant richness increased along the vegetation restoration succession: tussock grass < woody shrub < secondary forest < primary forest, in Huanjiang County, Guangxi. In soils with low bioavailable P, AMF may obtain P from less-bioavailable sources, via symbiosis with bacteria (e.g. Mosse et al. 1981), phosphatase activity (e.g. Dighton 1983), or release of exudates that enhance dissolution of P minerals, notably oxalic acid (e.g. Jurinak et al. 1986; Cannon et al. 1995).

Reductions in vegetation biodiversity in cultivated karst cause significant changes in soil nutrient pools, biochemical properties and soil microbial activity (microbial biomass, bacterial species richness and diversity, and enzyme activity; Zhang et al. 2006; Chen et al. 2012b; Li et al. 2014a). Cultivation disrupts soil aggregates and promotes the exposure of previously-protected SOM to microbial decomposition and loss (Qiming et al. 2003; Wang et al. 2015a), further diminishing the SOM-associated pool of nutrients (Hu et al. 2016; Jiang et al. 2006; Wang et al. 2015b). Xiao et al. (2017) studied five typical karst land uses in southwest China (enclosure land, prescribed-burning land, fuel-wood shrubland, pasture and cropland) and determined that the volume of large macro-aggregates and coincident stocks of SOC and total nitrogen (TN) were significantly reduced in those areas not subject to managed burning and cropland (under maize cultivation). Hu et al. (2016) reported that converting forest to cropland led to SOC losses of 19 - 38% down to 1 m depth in Huanjiang County, Guangxi, and Chen et al. (2011a) observed SOC and TN decreased significantly in the order: secondary forestland > scrubland and abandoned farmland > farmland, commercial forestland and forage grassland. Other soil nutrients, e.g. Ca and Mg, were observed to decrease in proportion to SOC during long-term cultivation (Jiang et al. 2006), are also important for healthy plant growth and play a role in SOM stabilisation by forming cation bridges with mineral surfaces in neutral and alkaline soils (Chen et al. 2011a). It is not clear whether concentrations of these cations can recover following cropland abandonment due to low rates of soil formation (see section 2.1).

4. Response of soil functions to agricultural abandonment under the ‘Grain for Green Programme’ (GGP) in the Chinese karst CZ

The focus of the GGP has been on the potential restoration of ecosystem integrity by allowing low-yielding cropland on slopes greater than 15° to revert to ‘natural’ vegetation where synthetic nutrient input has been withdrawn (Zhang et al. 2015; Wang et al. 2017). Each phase in the recovery gradient (see Text Box) is characterized by a unique plant community, i.e. sloping farmland: crop monocultures < abandoned sloping cropland: grasses and non-woody herbaceous species < secondary forest: woody shrubs and small trees < primary forest: mature trees and under-story species (Li et al. 2018). The observation and analysis of soil functions along this succession is a key focus of CZ research in the Chinese karst region. It can be inferred that the positive feedback between loss of soil by erosion, reduction in biological productivity, and reduction in biogeochemical processes is important in the process of karst landscape degradation towards rocky desertification. Nevertheless, the quantitative interdependencies of these processes are not sufficiently well constrained in theory or observations to permit explanation of the current state of the degradation gradient in the CZ or to predict the future trajectory towards recovery or degradation. For instance, in addition to exploring the effect of past erosion on CZ state as a dominant factor driving rocky desertification, it is also necessary to understand the process interactions, specifically, the relationship between loss of soil depth due to past erosion and weathering rates and nutrient release; and loss of soil depth and biological control of nutrient cycles. Furthermore, understanding the future trajectory of the CZ at each point along the gradient requires that the influence of current CZ state, e.g. soil aggregate stability and vegetation cover, on current erosion rates is quantified.

Successional studies of vegetation in karst showed greater plant diversity and productivity correlated positively with increased bacterial metabolic diversity (Cardinale et al. 2007). Xue et al. (2017) reported that the diversity, structure and co-occurrence of bacterial communities differed within soils of different land uses (i.e. grassland, shrubbery, secondary forest, pure plantation and mixed plantation). Bacterial diversity was positively correlated with pH and Ca^{2+}, and negatively with SOC, TN, and soil moisture; which highlights the importance of land-use driven biogeochemical properties in supporting microbial biomass and community structure. However, the metabolic functioning of bacterial communities in disturbed environments (in younger succession stages) may be less stable over the plant growth season (He et al. 2008) and longer term; Chen et al. (2012b) observed that bacterial diversity (measured using RFLP and16S rDNA sequencing) in karst soils allowed to revegetate naturally from cropland remained much poorer compared to a primary forest system even after 20 years of abandonment.

Nutrient storage and availability is one of the most important factors influencing the vegetation recovery in karst terrains with shallow soil (Rivera & Aide 1998; Hofmeister et al. 2002; Piao et al. 2005), largely due to limited availability of plant-available P rather than N in calcareous soils (Niinemets & Kull 2005; Liu et al. 2006; Hu et al. 2009; Wen et al. 2016). The low bioavailability of P in karst soils is expected due to the very low solubility of Ca-phosphate minerals at neutral to alkaline pH. Du et al. (2011) demonstrated that the karst vegetation species in a mountainous region in Puding County, Guizhou Province were generally P-limited or N- and P- co-limited and suggested that the soil N:P ratio could be an effective indictor for nutrient limitation in the karst ecosystems at the vegetation community level, rather than at tree species level. A study by Zhang et al. (2015) largely confirmed these findings, concluding that the secondary and primary forests are P-limited, and that shrubland is constrained by N and P or by other nutrients. However, they also provided observations that the grasslands within the region may be N-limited. It was proposed that nutrient recycling via litter decomposition and reabsorption is a primary mechanism for nutrient supply exploited through adaptation strategies by the dominant species in response to the low nutrient (in particular P) availability in karst soils (see section 3.2).

Little is known about changes in N stocks and distributions in former farmlands and recently regenerated forests under the GGP, particularly in the karst region. A shift in land-use from agriculture to forestry induces major changes in the N cycle, including inputs, internal cycling, and losses. The soil properties of former cropland in secondary forest are slowly modified towards conditions found in native forests because of a lack of intense cultivation (i.e. high fertilization rates, annual tillage, weed control) along with progressive vegetation succession (Zhang et al. 2012). In the initial phase of regeneration, former cultivated land retains an increased N status as a legacy of former fertilization, which supports persistent, relatively increased rates of mineralization and nitrification (Jug et al. 1999) but which is predicted to change over time as the source of N in soils switches from inorganic fertilisers to biological fixation. For example, the diversity of soil microbial groups associated with ammonia oxidation varied across a vegetation succession and were significantly increased in a primary forest compared with grass tussock, woody shrub, and secondary forest vegetation (Liang et al. 2014). Li et al. (2018) measured an increase in the overall abundance of nitrogen functional genes along a vegetation recovery gradient in a karst landscape, which correlated with available P and nitrate-nitrogen (NO_3 –N) content. Ammonia-oxidation was promoted whilst organic N decomposition was suppressed by N fertiliser in the farmed soils. By contrast, native primary forest and regenerated secondary forest soils had a greater capacity for N fixation and storage, although accompanied by greater nitrous oxide (N_2O) emission potential.

Soil organic carbon loss may be reversed following agricultural abandonment in degraded karst environments, allowing recovering ecosystems to act as net sinks for atmospheric CO_2 (Guo & Gifford 2002; Li et al. 2012a). Chen et al. (2011a) showed that, following agricultural abandonment, SOC recovered to primary forest levels after ~40 years at a rate of 1.38 Mg C ha^{-1} y^{-1}, with exchangeable Ca^{2+} and Mg^{2+} serving as the strongest predictors of SOC dynamics. Liu et al. (2015b) identified relationships between land use and SOC along a recovery gradient (grassland < shrubland < secondary forest < primary forest) using redundancy analysis, with significant C accumulation with vegetation succession, from 29 C g kg^{-1} in grassland to 74 C g kg^{-1} in primary forest. Soil organic carbon, available P, total N and plant richness in unmanaged ('natural') karst ecosystems increased in diversity along a gradient from tussock grassland to primary forest and were positively correlated with the abundance of AMF and

N_2-fixing bacteria (Laing et al. 2016), raising the potential to inoculate degraded soils using primary forest soils as a source of native rhizobia or manufactured spore preparations to accelerate karst soil restoration (Tian et al. 2008; Chen et al. 2012b).

Managing soils so that they are suitable for key groups of microbial populations is of fundamental importance for healthy ecosystem functioning as they drive ecosystem service delivery, including C and nutrient cycling (Doran & Zeiss 2000). Soil microbial community, pH and bacterial diversity also changed with ecological succession. Bacterial communities were found to be more sensitive to available organic substrates in the soil than fungal communities, whereas the latter are more sensitive to variations in soil pH (Feng et al. 2016). In addition, Xue et al. (2017) found that the diversity, structure and co-occurrence patterns in bacterial communities differed within soils of different land use, i.e. grassland, shrubbery, secondary forest, pure plantation and mixed plantation. Bacterial diversity was positively correlated with pH and Ca^{2+}, and negatively with SOC, TN, and soil moisture; which highlights the importance of land-use derived biogeochemical properties in supporting microbial biomass and community structure. Soil organisms (plants and microorganisms) with specific adaptations for nutrient fixation and scavenging, including the development of symbiotic relationships, hold potential to help restore the complex biogeochemical interactions vital for restoring CZ function in degraded karst landscapes.

5. Integration and identification of the key mechanisms underlying the delivery of ecosystem services and optimisation of land use in the Chinese karst CZ – the way forward

The rapid degradation rates of karst CZ restricts the sustainable development of soils and related services (Wu et al. 2011; Tang et al. 2013), and an enhanced mechanistic understanding of the CZ is needed to devise strategies for sustainable management and landscape regeneration. We are beginning to understand the geological, hydrological and ecological processes which control soil fertility and soil function in karst landscapes and how best to manage them to maximise ecosystem service delivery. Scientific advances are integral to the delivery of ecosystem and societal benefits, namely the provision of a rich evidence base for land management decision-making for stakeholders from the individual farmer to the state government. There are a number of areas that need to be tackled to fully understand the dynamics of karst ecosystems, with particular emphasis on its heterogeneous nature.

The majority of Chinese studies of the southwest karst CZ to date have taken a narrow approach to address a particular research question without given consideration to the wider local context or the fact that the nature of the underground network and its influence on soil processes. In essence, a wider assessment is required of the integrated geophysical-geochemical-ecological responses of the CZ to perturbations (i.e. spanning a gradient from undisturbed natural vegetation through human perturbed landscapes) to address key questions. Explicit consideration of plant-microbe-soil and plant-microbe-rock interactions is required to identify the biological controls on nutrient availability, soil formation and loss; accompanied by the quantification of the active lower boundary of the CZ along the perturbation gradient, to reveal the linkages between belowground channel network and biological activity. Deriving from the scientific context and direct observations there is a need to consider (1) the constraints on total plant productivity through the low provision of rock-derived nutrients; (2) the role of silicate rocks in controlling soil formation and ecosystem productivity; and (3) the determination of the tipping points in terms of soil storage and soil carrying capacity, below which biological activity becomes so low that CZ function becomes unrecoverable on decadal timescales. The understanding developed on the processes controlling ecosystem productivity in the CZ, can potentially be upscaled to provide a wider assessment of ecosystem function in southwest China.

Numerical models clearly represent essential tools in any attempt to generalise to larger scales. For example, established process-based C models, e.g. Roth-C (Coleman & Jenkinson 1996), are well-tested and have been used successfully to characterise national-scale C stocks in France (Meersmans et al. 2013). These models aim to mathematically describe the processes behind the observed SOC dynamics in relation to a wide range of controlling factors such as climate, land use, soil type and agricultural management, based on a theoretical soil C pool partitioning according to decomposition rate. Nevertheless, they have been little used in comparable karst landscapes and there is a pressing need to adapt the detailed descriptions of C pools and their depth distributions to test the capacity of established models to simulate the observed system behaviour in the karst CZ.

Recently-developed models have attempted to simulate properties that may be considered as emergent products of multiple processes. The development and calibration of one such model was a primary output of the Koiliaris River karst CZ research on Crete, Greece (Stamati et al. 2013; Giannakis et al. 2014). Those studies demonstrated that the coupled Carbon, Aggregation, Structure and Turnover (CAST) model has the potential to simulate soil structural development over decadal timescales and its influence on soil productivity. Soil organic carbon stocks have also been estimated at the national-scale (Belgium) using empirical models of the vertical distribution of SOC that could be related to environmental parameters (Meersmans et al. 2009). Despite the potential power of such approaches, they are less well established for mapping other soil properties such as macronutrients. There is a requirement to establish whether the C and macronutrient depth distributions in the karst CZ can be characterised using such empirical models and whether the spatial heterogeneity in depth distribution can be related to characteristics visible at the surface such as vegetation and rocky outcrop cover. This will shed further light on the controlling mechanisms and define the requirements to promote vegetation regeneration, sustainability and the reduction of long-term poverty associated with inappropriate agricultural practices on these fragile soils. At this time, the main policy is to abandon agricultural land to promote preservation and regeneration, which conflicts with the long-term supply and sustainability of food resources. It is imperative that we derive the knowledge and understanding of the CZ processes underpinning the healthy functioning of karst soils to support the delivery of regulating, supporting, provisioning and cultural ecosystem services in the iconic southwest China karst landscape.

6. Conclusions

Karst CZ degradation rates restrict the sustainable development of soils and related ecosystem services in the sub-tropical climate of southwest China (Wu et al. 2011; Tang et al. 2013). An enhanced mechanistic understanding of the CZ is necessary to devise strategies for sustainable management and landscape regeneration. Considerable areas of the Chinese karst appear to have passed the proposed ecological tipping point where all soil has been lost, and rocky desertification dominates (Wang et al. 2004a, 2014). Coupled with the threats from urbanisation, including the large-scale extraction of bedrock for construction, and the pollution of soil, water and air by the profligate use of agrochemicals to support NPP on degrading soils in the region, it is paramount that substantial academic resources are devoted to understanding the fundamental geochemical processes at play in the SW Chinese karst landscapes. This review of the current literature suggests that the knowledge base on which to build a structure of sustainable management approaches for rejuvenation of karst areas in SW China, to meet the needs of the local population including the preservation of this iconic cultural landscape, now and in the future, is rather patchy and urgently requires a mapping exercise based on developing a full CZ understanding. In particular, there is a critical need to account for the spatial heterogeneity of the rock-soil-(water)-plant-atmosphere system and its influence on the integrated delivery of ecosystem services.

The GGP recommends abandonment and natural regeneration of vegetation in degraded southwest China karst regions. However, to accelerate recovery, we recommend the development of strategies for ecosystem restoration that are designed and managed with consideration for specific plant adaptations to changing environmental conditions. For example, the spatial distribution characteristics of soil properties and rock fractures and their water storage and nutrient contents in different seasons, can be exploited and utilised by planting campaigns similar to those used in other degraded environments, including options for agroforestry to provide continued income for farmers (see review by Chazdon 2008). Importantly, to be able to translate this knowledge and understanding into management plans including a programme of education that are useable by the local communities at scales of relevance for regional planning and poverty alleviation, it is essential that the knowledge gained is applied at scales much larger than the measurement domain, and integrated into a cross-China programme that links sustainable management of landscapes for production and industry with the quality of life for the human population.

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Figure 1

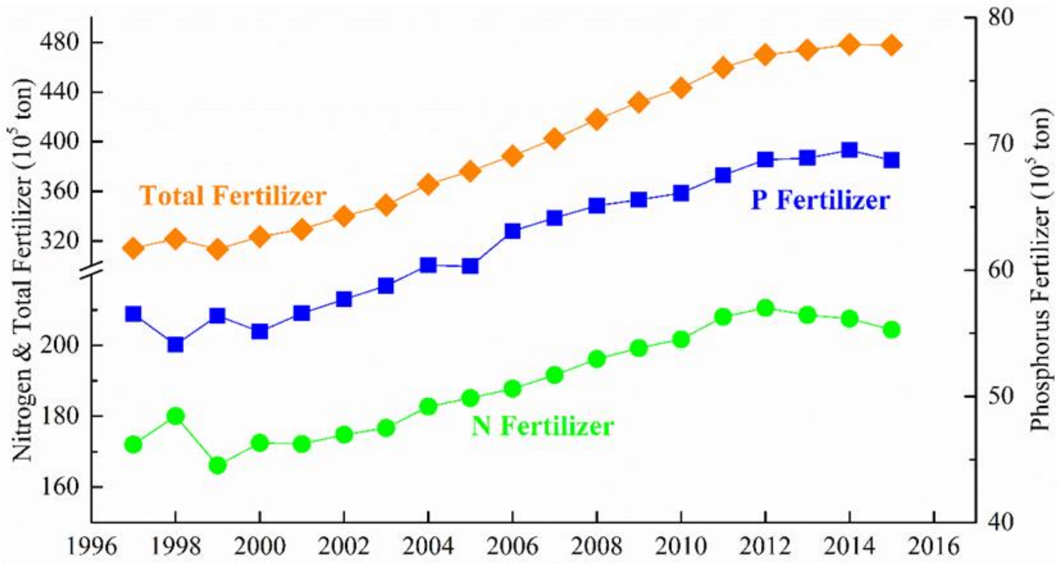


Figure 1 Fertiliser use (10^5 tons per year) in southwest China from 1996-2016. Nitrogen and Total Fertiliser values shown on primary vertical axis, phosphorus fertiliser values shown on secondary vertical axis). Total fertilizer is sum of nitrogen, phosphorus, potash and compound fertilizers. Data from http://www.stats.gov.cn/english/.

Figure 2

Figure 2 Increasing anthropogenic pressure on karst terrain through cultivation in China has led to the progressive use of marginal lands for cultivation (Chenqi and Chenjiazhai, Puding County, Guizhou Province) (Credit: Jennifer A. J. Dungait and Sophie M. Green).

Figure 3

Figure 3 Example of soil-filled underground fissure and crevice, which have been exposed overtime (Credit: Jennifer A. J. Dungait).

Figure 4

(a)

(b)

Figure 4. Examples of typical farmed karst landscapes in southwest China with (a) minimal rocky desertification and (b) extensive rocky desertification (credit: (a) Sophie M. Green and (b) Dali Guo).

Figure 5

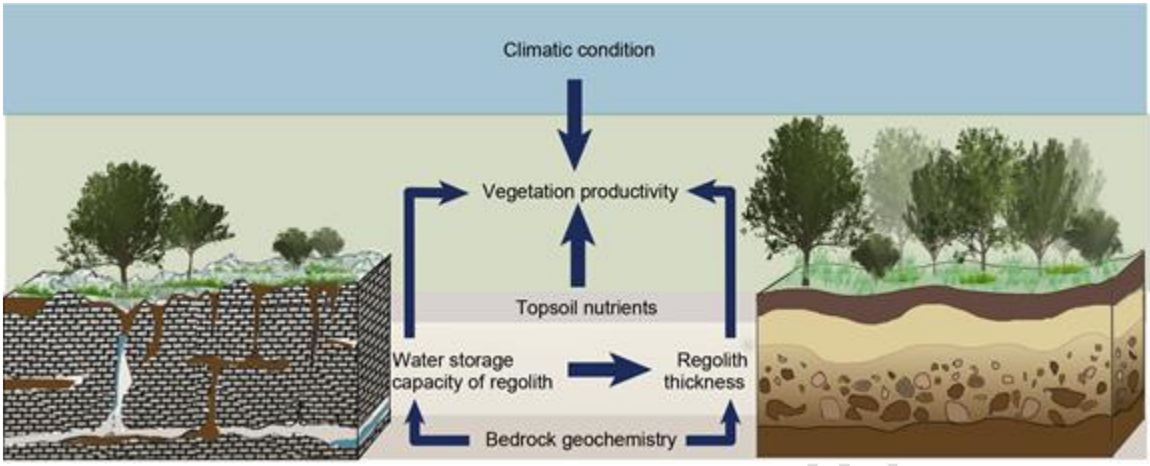


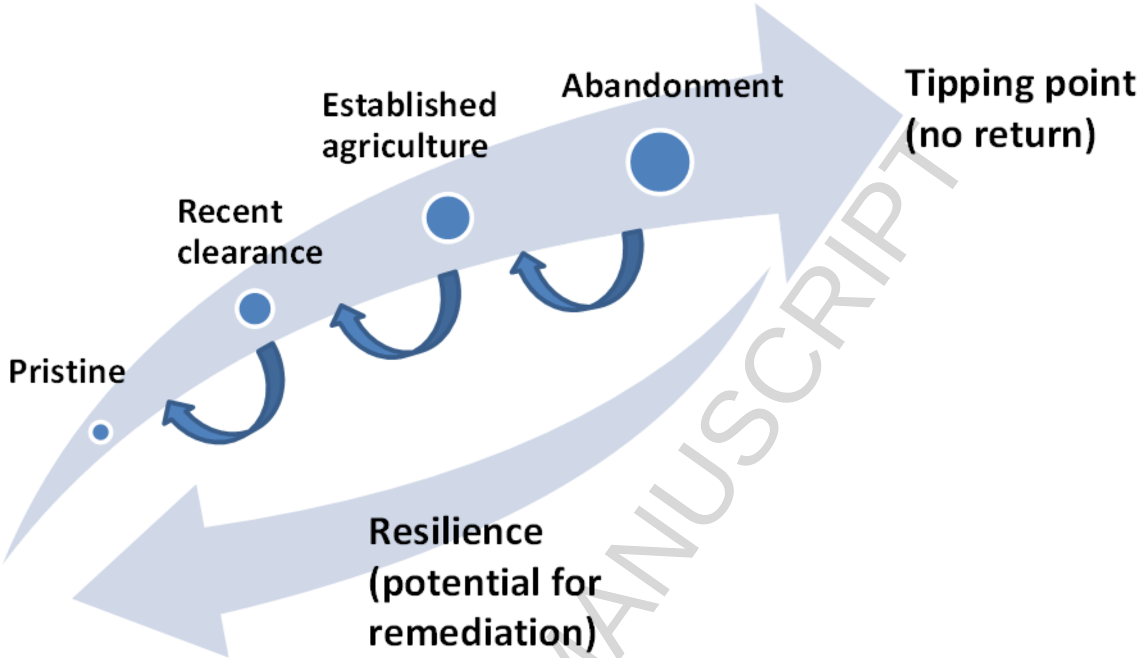
Figure 5 Conceptual models of a karst (left of figure) and non-karst (right of figure) Critical Zones in southwest China. Karst CZ is characterised by thin spatially heterogeneous soils (resulting in lower vegetation production and water storage capacity) and significant linkage from surface to complex underground epikarst system created by carbonate rock dissolution (i.e. bedrock geochemistry). Differences in nutrient availability between karst and non-karst soils is dependent on the bedrock geochemistry – see section 3.2 (Credit: Zhian Jiang).

Figure 6

Figure 6 Examples of roots interactions between plant roots and carbonate rocks in Guizhou, Southwest China.

TEXT BOX

Stages of ecosystem degradation in Chinese karst ecosystems



A perturbation gradient can be used to characterise the physicochemical-biological changes during 5 stages in ecosystem degradation in Chinese karst CZ after land use change to agricultural land use. The figure shows a conceptual diagram of the degradation gradient, potential recovery between stages (small dark blue arrows) and the role of the tipping point (although not yet explicitly characterised for karst soils).

Stage 1: PRISTINE

Under natural or semi-natural conditions, the limestone surface is mantled in soil and the soil resource extends naturally into deep fissures. Vegetation distribution may be optimally matched to the spatial distribution of soil. For example, large trees extend their roots deep into the soil stores in rock fissures, accessing water and nutrients that would otherwise be inaccessible. Natural and comprehensive vegetation cover (i.e. litter, canopy and roots, and mycorhizal fungi) protects soil resources by moderating the impact energy of rainfall (critical during the monsoon) and mediates gradual water infiltration, potentially reducing erosion rates. The greater residence time of water in the CZ and relatively rapid rates of biological activity could enhance rock weathering rates, releasing vital elements to the soil solution that supports soil ecological function and Net Primary Productivity (NPP).

Stage 2: RECENT CLEARENCE

Natural vegetation is removed (deforestation) and converted to arable farmland. The exposure of bare soil to intense sub-tropical rainstorms during the monsoon significantly accelerates potential rates of soil structural degradation, especially losses of surface soil by water erosion. The removal of deep-rooted trees and shrubs may limit biological activity to surface soil layers that are those most vulnerable to erosion, cutting off access to deep soil resources including stored water and nutrients. The death of deep roots and associated soil microorganisms, including mycorrhizal fungi, that bind soil, removes the biological modulation of hydrological cycle including energy dissipation and downward water flow momentum, creating positive feedback between increased soil and water loss and further reductions in biological activity. Ultimately, high rates of infiltration cause rapid leaching of nutrients to below the rooting depth of crop plants and ultimate loss from the karst systems through the sub-surface flow pathways. Reduced or absent biological activity reduces weathering rates and the replenishment of natural nutrient pools.

Stage 3: ESTABLISHED AGRICULTURE

As the structural stability of the deeper karst soil (i.e. those contained within fissures / crevices) declines in the absence of roots and mycorrhizal fungi, there is increased potential for movement of soil from fissures into sub-surface channels. From a management point of view, with limited information on soil depth and soil moisture, land users cannot match the crops or other plants to the CZ structure below ground to maximize new plant growth and promote the rapid recovery of underground root distribution and to reduce the loss of critical soil resources.

Stage 4: ABANDONMENT

Progressive soil destabilisation leads to greatly accelerated soil loss both via sub-surface and surface pathways and, ultimately, leads to the CZ reaching a tipping point with total loss of soil from deep fissures and the soil resource limited to discontinuous pockets of shallow depth, and extensive exposure of bare rock, i.e. rocky desertification, with little potential for pedogensis in timescales relevant to human activity. Farmers abandon the land because NPP is effectively halted due to lack of soil as a growth medium.

Stage 5: POTENTIAL FOR REMEDIATION?

Clear evidence of environmental degradation and its damaging consequences in SW China, including intrinsic value of the landscape for the economies of the culturally diverse local populations, has led to an increasing policy focus on the potential to rehabilitate the landscape. There is a clear socioeconomic imperative to understanding the soil processes and ecosystem services within the karst landscapes of SW China. Since the implementation of agricultural abandonment under the GGP, secondary plant communities have been in the process of succeeding toward the state of the original "natural" forests (Tang 2010; Tang et al. 2010) and observed changes in soil quality as well as in vegetation and microbial composition and function have been reported.

Table 1 Area of rocky desertification in southwest China in 2000. Adapted from Jiang et al. (2014).

Provinces and regions	Total land area (10^5 x km^2)	Area of rocky desertification (10^5 x km^2)	Rocky desertification as (% total land area)
Yunnan	38.4	3.3	8.7
Guizhou	17.6	3.3	17.1
Guangxi	23.6	2.7	11.5
Hunan	21.2	0.5	2.4
Chongqing	8.2	0.5	5.6
Hubei	18.6	0.4	2.3
Sichuan	48.1	0.4	0.9
Guangdong	17.7	0.2	1.4
Total	**194.7**	**11.4**	**5.8**